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## Numerical and experimental analysis of resistance projection welding of square nuts to sheets

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### Abstract

Projection welding of nuts to sheets is a widely utilized manufacturing process in the automotive industry. The process entails challenges due to the necessity of joining different sheet thicknesses and nut sizes made from dissimilar materials, and due to the fact of experiencing large local deformations ranging from room temperature to above the melting point. Heating is facilitated by resistance heating and is highly influenced by the contact area resulting from the amount of deformation, which is also temperature dependent due to material softening and frictional conditions. Resort to new materials and applications require a new level of understanding of the process by combining finite element modelling and experimentation. This paper draws from the challenge of developing a three-dimensional computer program for electro-thermo-mechanical modeling of resistance welding and presents, as far as the authors are aware, the first ever three-dimensional simulation of the projection welding of square nuts to sheets by means of finite element analysis. Results are compared with experimental observations and measurements produced by the authors with the aim and objective of assessing the accuracy, reliability and validity of the theoretical and numerical developments. Numerical simulations support the evaluation of the experiments by providing detailed information on the process like the initial heating location and the following temperature development, and allowing to analyze the weldability of the square nut to the sheet under different operating conditions.

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**Keywords:** Resistance projection welding; Square nuts; Experimentation; Finite element method; Friction

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## 1. Introduction

Projection welding of bolts and nuts to sheets is a critical manufacturing process in the automotive industry (Larsson and Bengtson, 2007). Typical applications comprise the assembly of components such as front and rear axles, seat belts and steering columns, among others. The process is also widely used to fabricate machine parts, electrical and electronic equipment, and home appliances. The focus of this paper is the projection welding of square nuts to sheets, where the square nut projection legs that allow current concentration and welding can take various shapes within the DIN 928 (2013) standard. The variety of shapes stem from the different processes that are commonly utilized to fabricate the nuts. Some nuts are directly obtained from forging while others are subsequently machined to their final shape. As a result of this, the initial contact area between the square nut and the sheet varies for different nuts of the same overall size. This uncertainty is commonly acceptable in industry because the area towards the bulk part of the nut is considered more important than the exact shape of the tip of the projection, but it often leads to selection of welding parameters exclusively based on accumulated experience and trial-and-error procedures.

When considering the importance of projection welding of nuts to sheets in industry, it is surprising to conclude that there has been almost no systematic investigation published in the open literature. One of the few existing publications in the field is due to Tolf and Hedegård (2006) who investigated welding of three different M6 and M8 nuts to high and ultra-high strength sheets. Subsequent publications by Larsson (2008) and Ringsberg et al. (2008) examined published experiments and the influence of the geometry and dimension of the nuts on fatigue life. The first attempt to combine experimentation and numerical modeling of projection welding of nuts to sheets was carried out by Linden (2010) who utilized the finite element computer program SORPAS. He concluded on the necessity of SORPAS being further developed to be utilized as a computational tool to improve the weld nut geometry and the overall joint strength. To the authors' knowledge, there are no further investigations on the numerical simulation of industrial projection welding of nuts to sheets. This paper is built upon the newly released SORPAS 3D finite element computer program (Nielsen et al., 2012), and is mainly focused on the implementation of frictional contact between parts to be welded. Comparisons between numerical predictions and experiments give support to the presentation.

## 2. Numerical model

The numerical modeling is based on a coupled electro-thermo-mechanical finite element computer program. The mechanical module solves the deformation and stress fields at the beginning of each step, followed by a strong coupling between the electrical and thermal modules. The electrical module provides a current density field that leads to heat generation due to Joule heating. The heating and the heat conduction and transfer between objects are calculated in the thermal module.

### 2.1. Underlying mechanical module

The underlying mechanical module is briefly introduced in this section, while Nielsen et al. (2012) is referred to for further details on the electrical and thermal modules. The mechanical module is based on the irreducible finite element flow formulation, which is written as follows in its weak variational form,

$$\int_V \bar{\sigma} \delta \bar{\epsilon} dV + K \int_V \dot{\epsilon}_{ii} \delta \dot{\epsilon}_{ii} dV - \int_{S_t} t_i \delta u_i dS + \sum_{c=1}^{N_c} P g^c \delta g^c = 0, \quad (1)$$

covering domain volume  $V$  with arbitrary variations in velocity  $u_i$ , where  $\bar{\sigma}$  is the effective stress,  $\bar{\epsilon}$  is the effective plastic strain rate, and  $K$  is a large positive number (here  $K = 10^6$ ) imposing incompressibility by penalizing volumetric strain rate  $\dot{\epsilon}_{ii}$ . The third term is related to surface tractions  $t_i$  on surface  $S_t$ . The last term

penalizes gap velocities  $g^c$  in  $N_c$  contact pairs through a penalty factor  $P$  (here  $P = 10^6$ ). The application of the last term is discussed in more detail in the following subsection.

## 2.2. Contact modeling

The mechanical contact involves penalizing normal gap velocity through the last term in (1) if otherwise leading to penetration in the contact pair. Tangentially, gap velocity is also penalized to enforce full sticking until the resulting shear stress in the contact pair exceeds that associated with frictional sliding. When frictional sliding is to occur, the penalization of tangential gap velocity is omitted and the frictional stress is applied as surface traction on each of the contacting objects through the third term in Eq. (1). The frictional stress is evaluated by either  $\tau_f = \mu \sigma_n$  based on the Amonton-Coulumb law or by the law of constant friction  $\tau_f = mk$ , where  $\mu$  is the friction coefficient,  $m$  is the friction factor,  $\sigma_n$  is the normal pressure and  $k$  is the shear flow stress. Considering the von Mises yield criterion and assuming the change between the two friction laws at  $\sigma_n / (\sqrt{3}k) = 1$ , the relation between the friction coefficient and the friction factor is  $\mu = m / \sqrt{3}$ . The opposite direction of the relative velocity  $\mathbf{v}_r$  determines the direction of the friction stress. To avoid the singularity in the derivative of the relative velocity in the finite element implementation, the following expression is used for the applied friction stress,

$$\tau = -\frac{2}{\pi} \tau_f \cdot \arctan\left(\frac{\mathbf{v}_r}{v_0}\right), \quad (2)$$

which is continuous in its derivative and resembles the friction stress accurately when the constant  $v_0$  is chosen small enough. Eq. (2) was proposed by Chen and Kobayashi (1978), and the integration follows the 5x5 Gauss quadrature presented by Barata Marques and Martins (1990).

Electrical and thermal contact is implemented by penalizing differences in the electrical potential and the temperature, while having layers of elements modeling the physical contact conditions (Nielsen et al., 2012).

## 3. Experimental setup

The experiments were carried out in an Expert 170 kVA welding machine equipped with a Harms & Wende HWI 2000 control unit supplying a 1 kHz middle frequency direct current, which is practically acting as direct current. The load is applied hydraulically through a number of disc springs to have good mechanical follow of when the projections collapse. Fig. 1(a) shows the experimental setup in the machine, Fig. 1(b) shows the positioning of the square nut and Fig. 1(c) the positioning of the sheet.

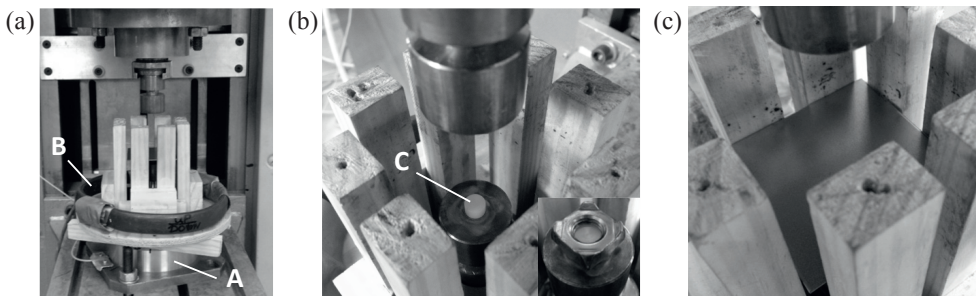


Fig. 1. (a) Experimental setup in the resistance welding machine including wooden guidance system, load transducer A and Rogowski coil B; (b) Placement of square nut on electrode by centering pin C; (c) Placement of sheet on square nut projection legs.

Standard, forged M10 square nuts (Fig. 2(a)) and simplified, machined square nuts (Fig. 2(b)) with well-defined dimensions and known material, steel S235JR+AR, were welded to 1.5 mm squared DC06 deep drawing steel

sheets between two type C0 copper alloy electrodes. The simplified square nuts are used in the comparison with the numerical simulations (using the material database available in SORPAS 3D version 3.3) by evaluating the cross-section indicated in Fig. 2(c) (refer to the dashed line on top of a final projection weld of a simplified nut to a sheet). The experimental cross-sections were obtained by cutting, grinding and polishing.

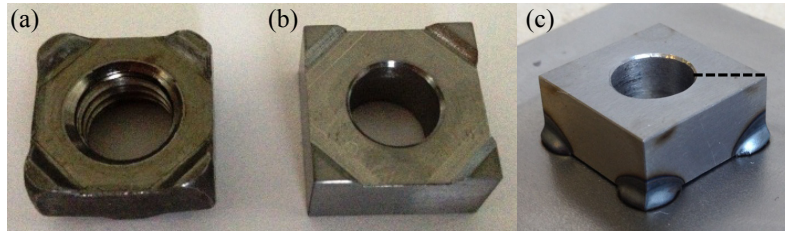


Fig. 2. Photograph of (a) standard M10 square nut; (b) simplified square nut made of steel S235JR+AR; (c) Example of a simplified square nut welded to a sheet. The dashed line indicates the cross-section that will be evaluated in Section 4.

#### 4. Results

The projection welding of square nuts to sheets are evaluated by their setdown and the cross-sectional deformation. The setdown  $S$  is defined as the relative deformation of the projection, which is simplified as follows in order to have well defined measurements,

$$S = \frac{A - B}{A} \cong \frac{A - (h - c - t)}{A}, \quad (3)$$

where parameters are defined in Fig. 3 by the initial projection height  $A = 1.2\text{mm}$  and the final projection height  $B$ , which is determined from the total final height  $h$ , the bulk height  $c = 7.8\text{mm}$  and the sheet thickness  $t = 1.5\text{mm}$ .

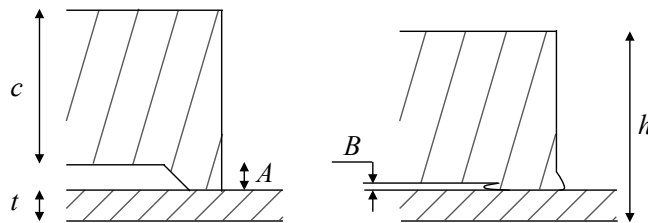


Fig. 3. Parameters for definition of setdown.

The setdown as function of weld current is presented in Fig. 4 for projection welding of the standard square nut and the simplified square nut. The electrode force was 6 kN and the current were kept during 180 ms. At two current levels, 12 kA and 17 kA, the same conditions were simulated by finite element analysis. The simulated setdowns for the simplified square nut are shown in Fig. 4 with intervals covering different treatments of mechanical contact. Frictionless and full sticking conditions were simulated for having the two extreme assumptions and frictional contact conditions with  $m = \{0.2, 0.4, 0.6, 0.8\}$  were simulated to cover contact assumptions in-between the two extremes. Comparing the setdown, it appears that the deformation is overestimated in the simulations, although having a slight overlap with experiments at 17 kA weld current. However, it is worth noting that an electrode movement of 0.1 mm corresponds to more than 8 % on the scale of setdown.

Cross-sections of the welded nuts at 17 kA weld current are shown for the standard square nut in Fig. 5(a) and for the simplified square nut in Fig. 5(b). Both cases show a heat affected zone covering the projection and part of

the bulk material of the nut near the projection, while little or no heat affected zone is observed in the sheet. This is a result of high heat conduction away from the sheet through the electrode. No melting is observed, and the material has only been heated to its mushy state, similar to solid state, friction welding. Tolf and Hedegård (2006) conclude similarly on the basis of their experiments with square nut welding.

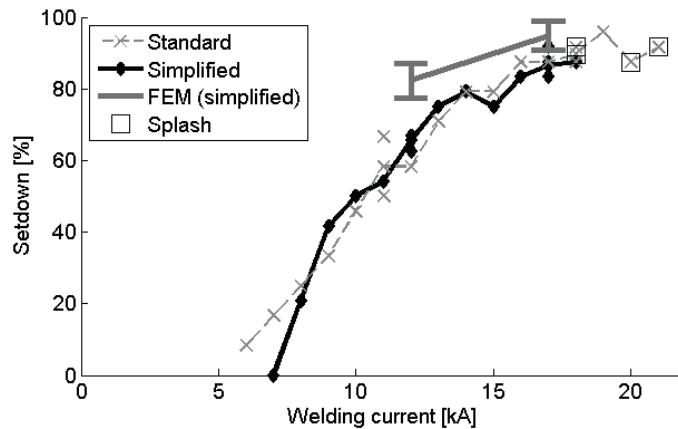


Fig. 4. Experimental setdown for the standard and simplified M10 square nuts at different current settings. FEM predicted setdown for the simplified nut welding is shown at two weld currents.

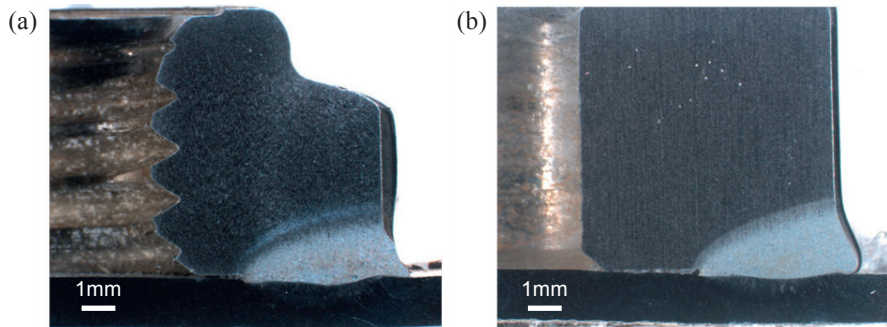


Fig. 5. Experimental cross-sections for weld settings comprising 17 kA weld current during 180 ms under an applied electrode force of 6 kN. (a) Standard square nut welded to sheet; (b) Simplified square nut welded to sheet.

The finite element predicted projection weld of the simplified square nut to sheet is shown in Fig. 6 by the evaluated cross-section. Three contact conditions are included; namely simulation with assumption of frictionless contact (Fig. 6(a)), with frictional sliding due to  $m=0.80$  or correspondingly  $\mu=0.46$  (Fig. 6(b)), and with assumption of full sticking (Fig. 6(c)). The predicted cross-sections in Fig. 6 are to be compared with the experimental cross-section in Fig. 5(b).

It appears that the assumption of frictionless contact results in too much deformation of the projection leg because of lack of mechanical resistance in the collapse. Conversely, the assumption of full sticking leads to overestimation of the heat because the expansion of the contact area is underestimated. Due to the excess of heat, the softening of the material leads to a subsequent collapse of the projection leg and to overestimation of the setdown. The simulation of frictional sliding provides results in-between the two extremes in terms of the dynamically developing contact area, while resulting in less setdown in better correspondence with the experiments. The frictional sliding provides mechanical resistance towards collapse of the projection, while allowing the expansion of the contact area to avoid overestimating the heat due to current concentration.

From a pure geometrical comparison, the simulation of frictional sliding also provides results in-between the frictionless and full sticking assumptions (compare projection contours in Fig. 6 with reference to the dashed line).



The simulation with frictional contact (Fig. 6(b)) results in 91% setdown, which can be compared to the three experiments having setdowns range from 83 to 92%.

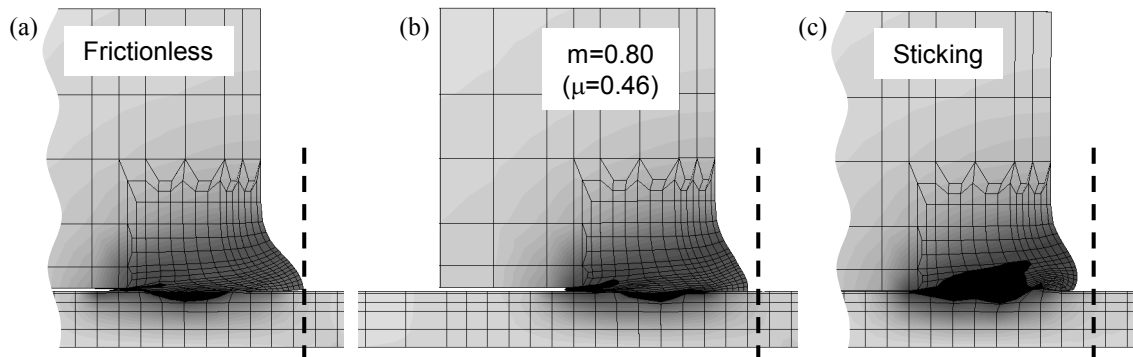


Fig. 6. Finite element predicted cross-sections for weld settings comprising 17 kA weld current during 180 ms under an applied electrode force of 6 kN. Different contact assumptions are simulated, (a) Frictionless; (b) Frictional with a friction factor  $m=0.80$  ( $\mu=0.46$ ); (c) Full sticking.

## 5. Conclusions

Numerical and experimental evaluations of the resistance projection welding process are presented for joining of square nuts to sheets. Comparisons between numerical predictions and experimentally obtained cross-sections are presented and evaluated by means of the resulting shape of the projections and the overall setdown. The numerical simulations are based on an electro-thermo-mechanical finite element computer program. Besides known importance of electrical and thermal contact resistances in the interfaces between objects, this paper put focus on the necessity of modeling frictional sliding in the simulation of resistance projection welding involving sliding during the collapse of projections. A new implementation of friction between deformable objects in the finite element flow formulation is presented, and results are given between the extreme cases of frictionless and full sticking conditions. It is shown that modeling of frictional contact improves the simulations, and it is discussed how friction influences the dynamics of the process in terms of contact area formation and heat generation.

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